The Analysis of Temperature and Stress in GaN Devices using Raman Spectroscopy

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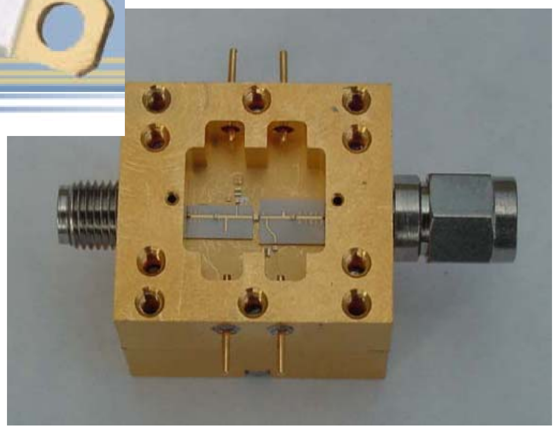
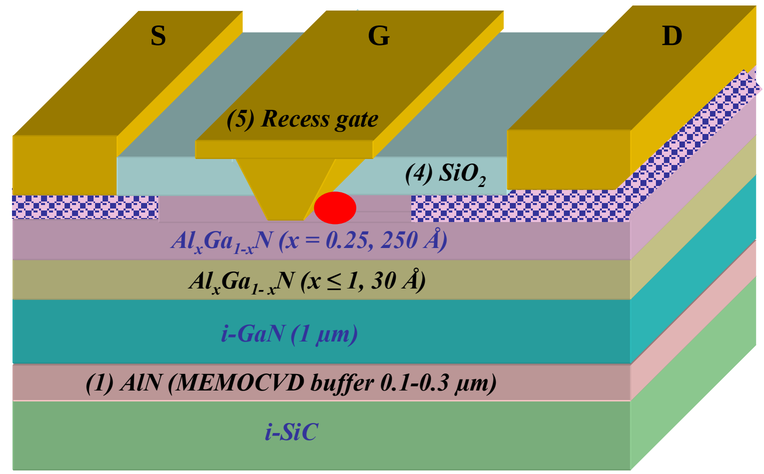
In support of the Air Force MURI:
A 21st Century Approach to Reliability
and
AFRL PACE Program

Wide Band Gap RF and Power Electronics

GaN HFETs
and
RF modules



WiMax Base Stations



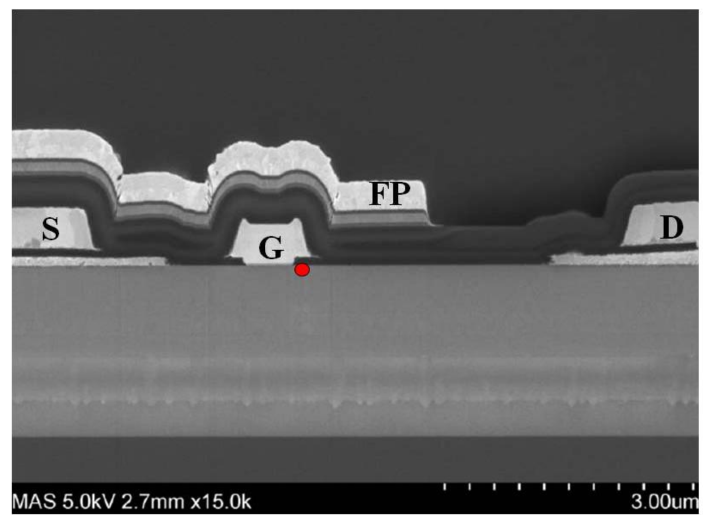
Develop new RF micro/millimeter wave applications using GaN

<u>Top Issues for deployment: Reliability and Thermal Management</u>

-Large power densities in device---intense device heating.

Has dramatic impact on device performance

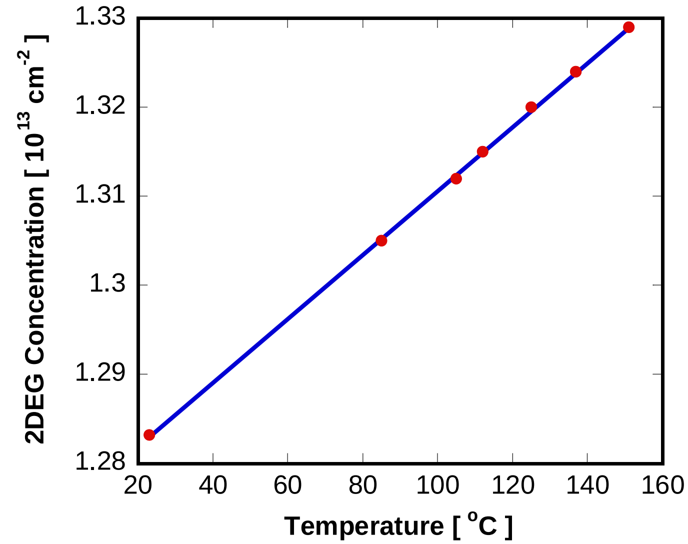
-degradation of contacts, defect creation, etc.

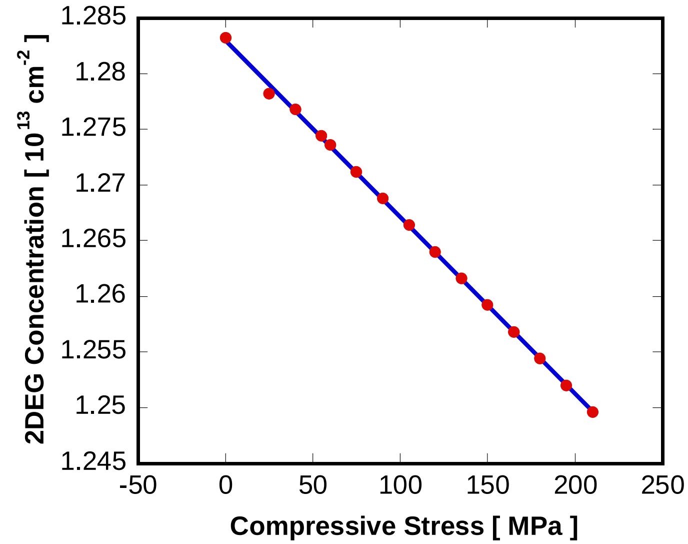


2DEG, Temperature, and Stress

- Temperature and stress significantly affect the 2DEG concentration of an HEMT.
- ***Performance*** is reduced by a 3% power reduction with even small loads (10% considered failure) [1].
- ***Reliability*** is affected by these parameters as well:
  - **Stress**: Life reducing cracking in device occurs in response to elastic effects.

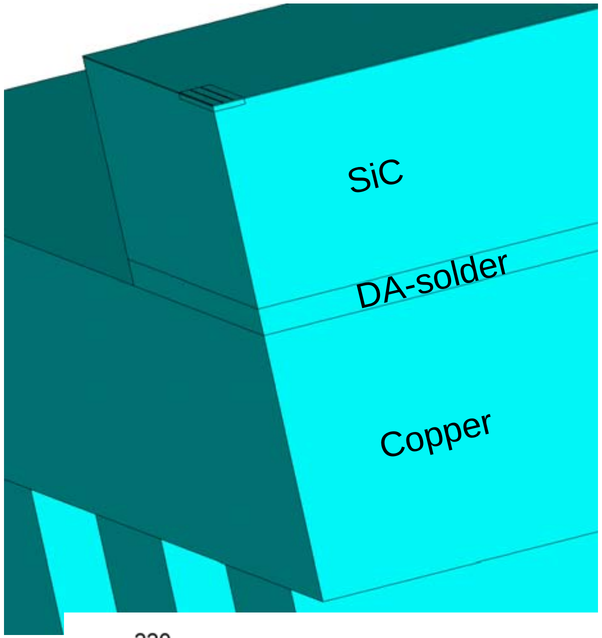
Takeaway: *Temperature and stress are inextricably linked to performance and reliability.*

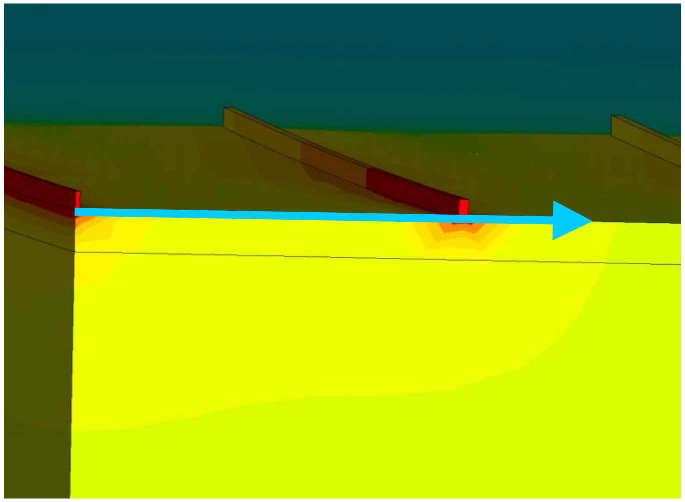


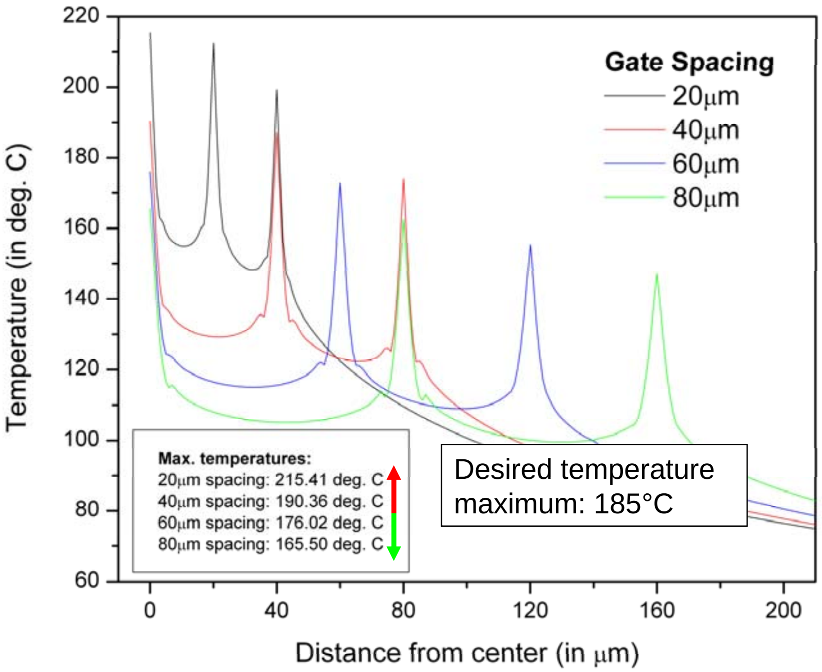


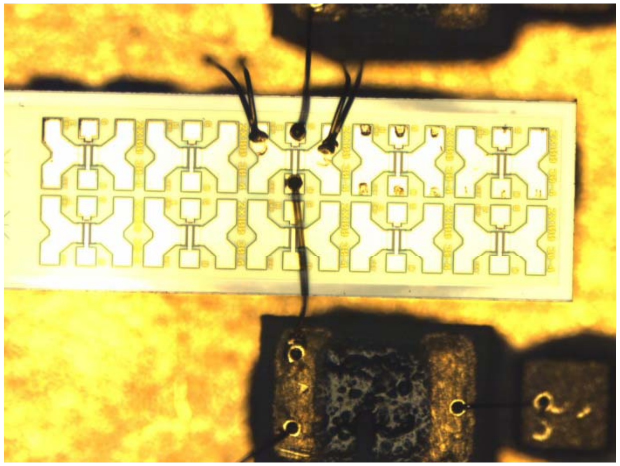
[1] *E. R. Heller, Electron Devices, IEEE Transactions on, vol. 55, no. 10, pp. 2554-2560, 2008.*

Thermal Modeling of GaN HFETs



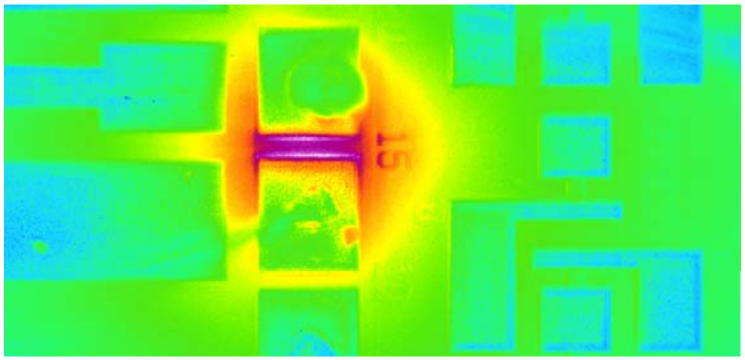


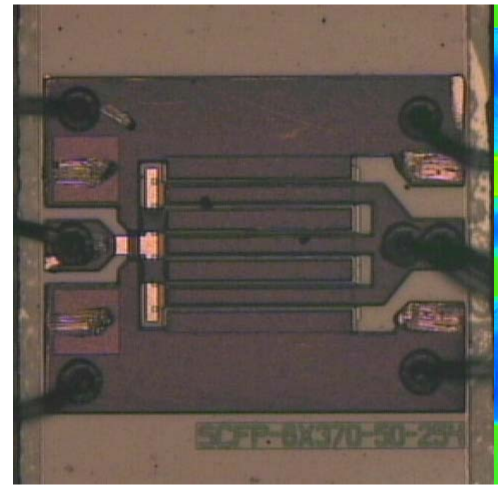




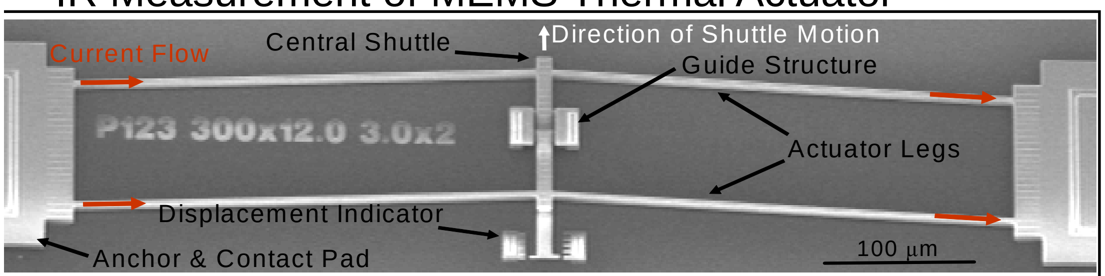
Temperature Measurements in GaN Devices

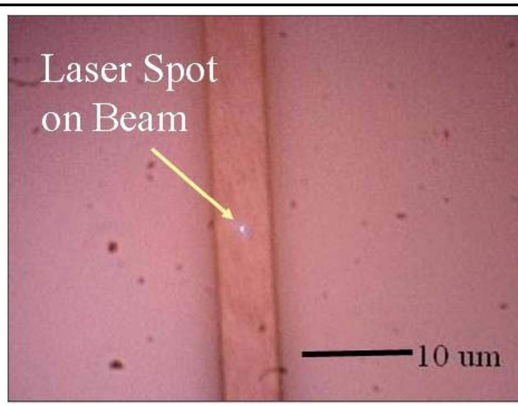
IR measurement of GaN on SiC TLM



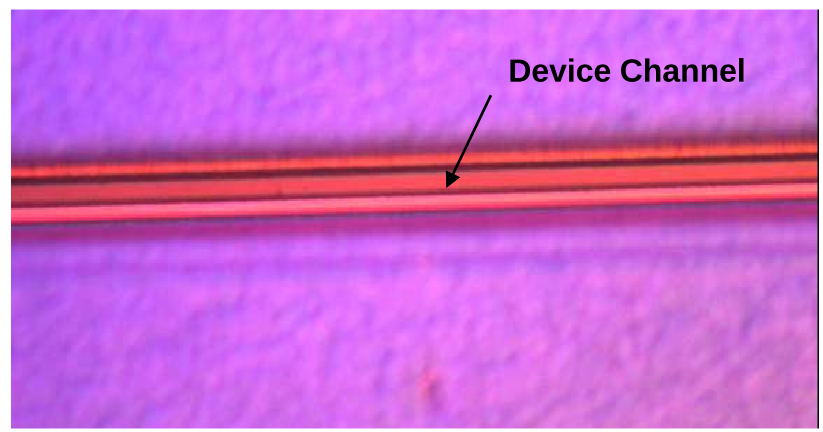


IR Measurement of MEMS Thermal Actuator





Measurement of HEMT Devices



Measurement of Channel Region:
Often not possible with IR

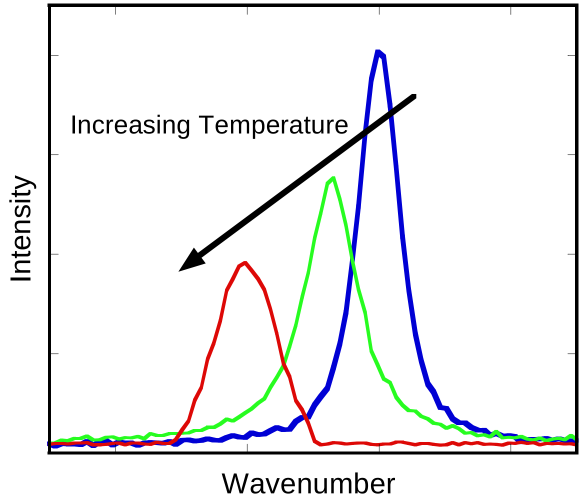
Micro-Raman Spectrum

Raman Spectroscopy probes the vibrational frequency and scattering of zone centered optical phonons in GaN.

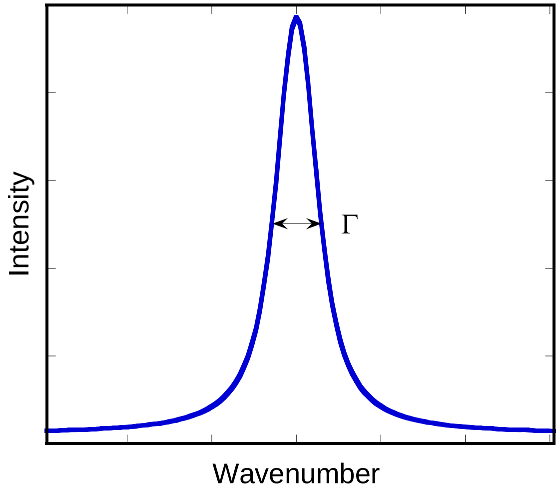
Also probes the equilibrium phonon population through the Stokes/Anti-Stokes ratio.

We can measure temperature by the following characteristics:

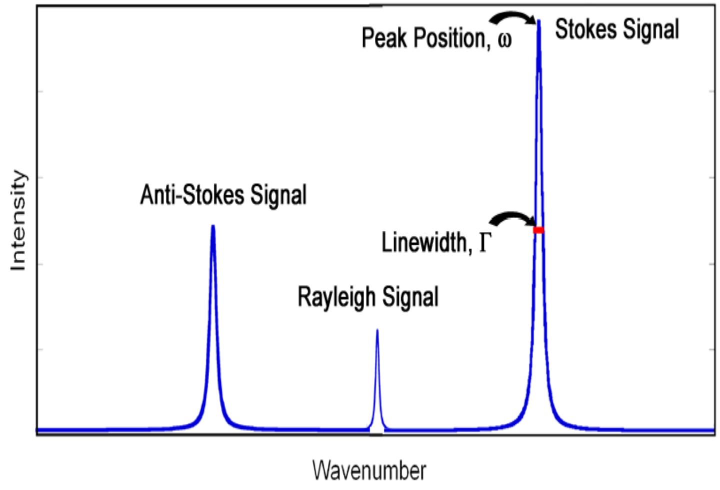
Peak shift (T_ω)



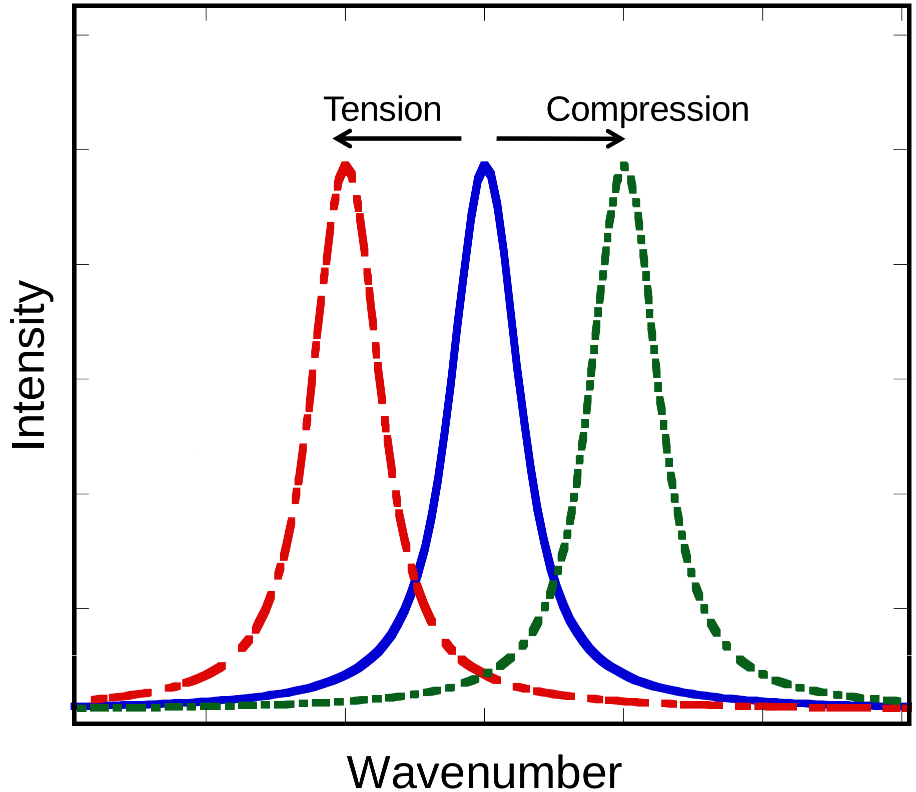
Linewidth variation (T_Γ)

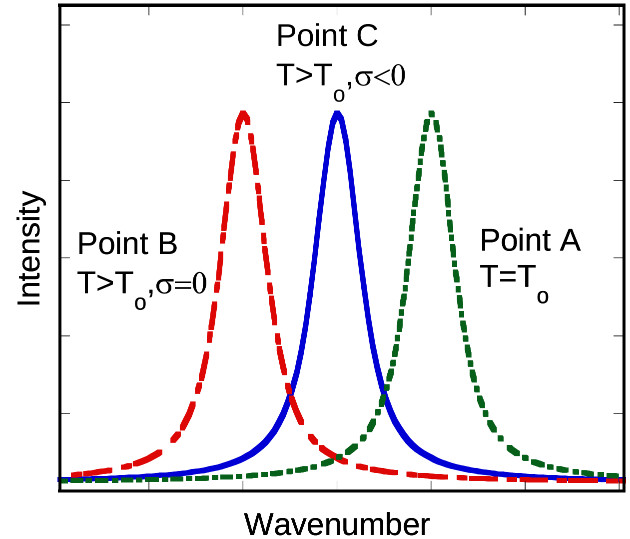


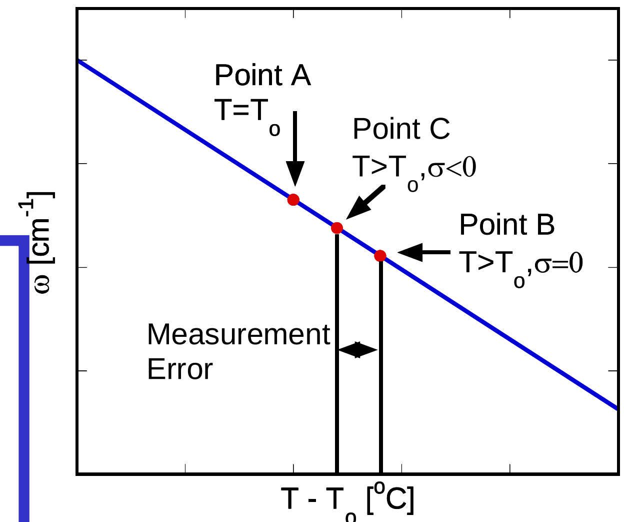
Intensity Ratio (T_R)



Raman Thermometry: Peak Shift







Under localized heating, a sample starting at point A will increase to a temperature at point B. The raman peak will want to shift to point B, but the presence of a compressive stress can cause the raman peak to shift only to point C. Compressive stresses counter act the movement of the peak with increasing temperature.

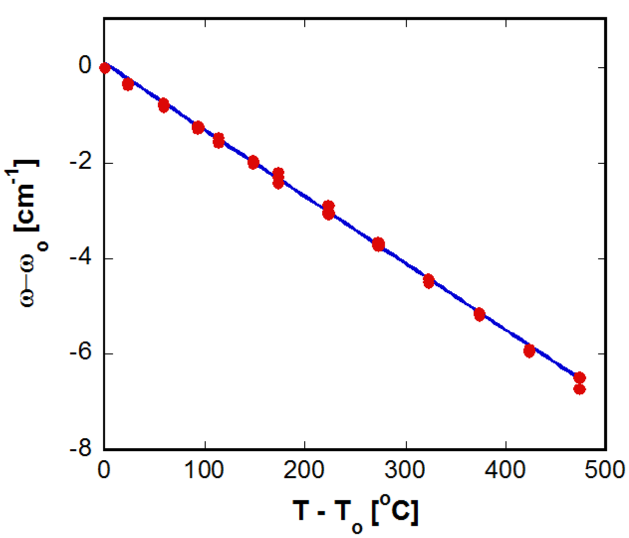
Solution: A separate aspect of the spectrum which is unaffected by stress.

Calibration: Temperature Dependence

- Temperature response is measured from 24-500ºC
- Peak shift and linewidth may be measured relative to a reference
- Intensity ratio must be measured using an extensive Ratio

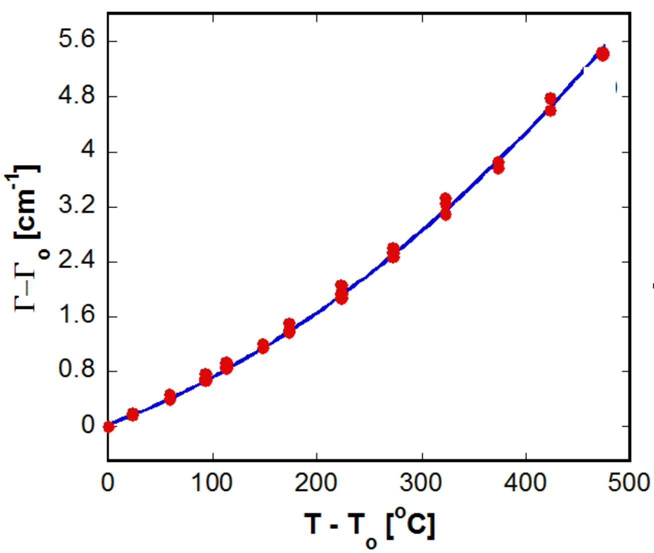
Peak Shift

$$\Delta\omega = A\cdot(T - T_o)$$



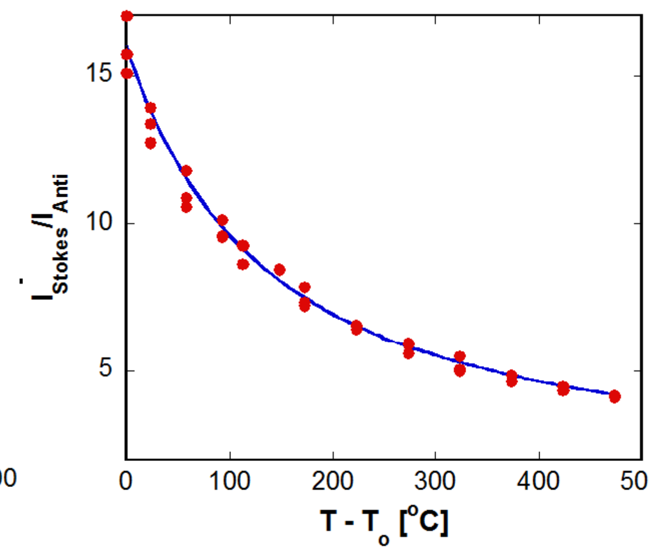
Linewidth

$$\Delta\Gamma = B(T - T_o)^2 + C(T - T_o)$$



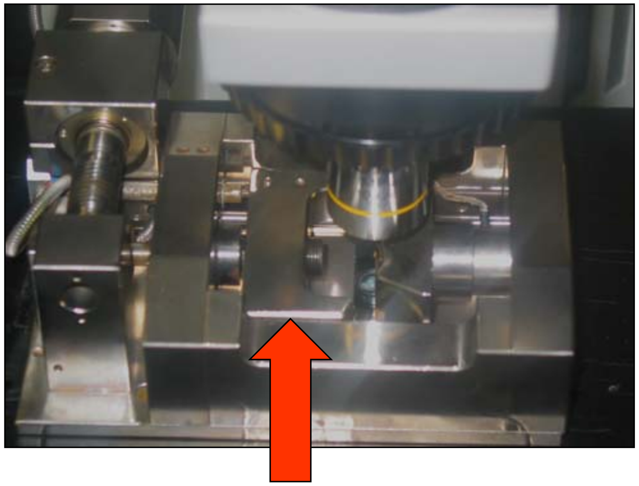
Ratio

$$I_{Stokes}/I_{Anti} = G\cdot e^{\left(-\frac{H}{T}\right)}$$



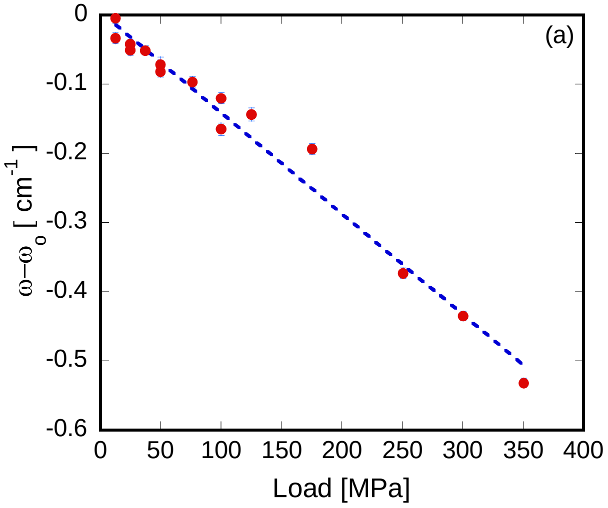
Calibration: Stress Dependence

- Tensile bending experiments on sample up to 350 MPa.
- Both Linewidth and Stokes/Anti-Stokes Ratio are independent of applied stress.
- <u>Conclusion:</u> Linewidth & Ratio may be used for measurement of temperature independent of thermoelastic stress

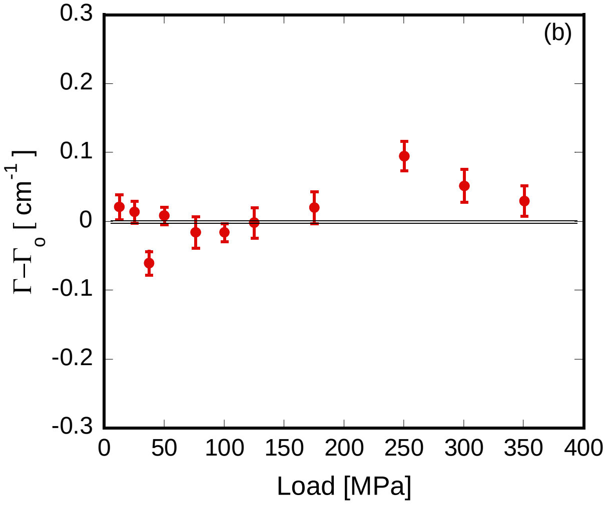


5000N 4-point Bending Fixture w/ sample

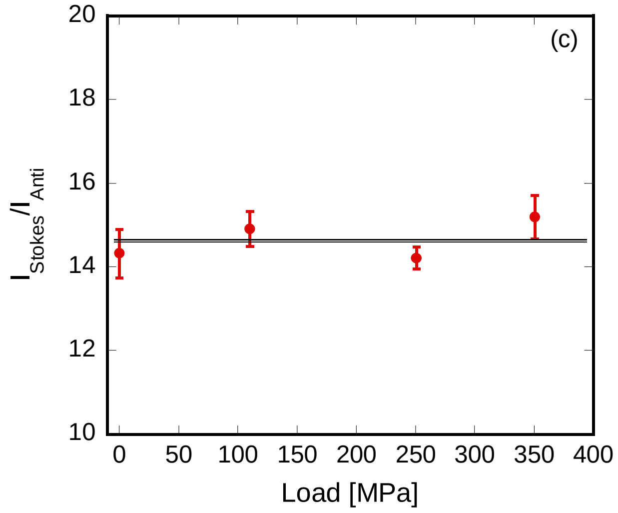
Peak Shift



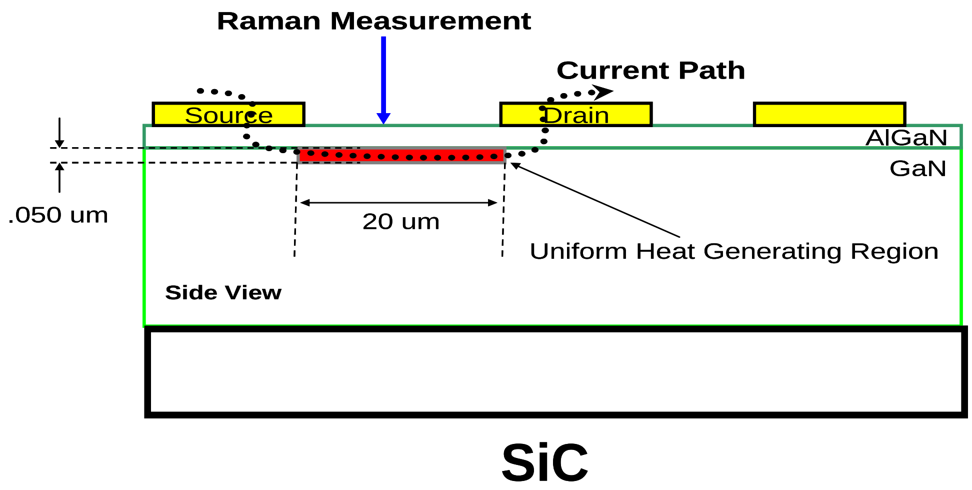
Linewidth

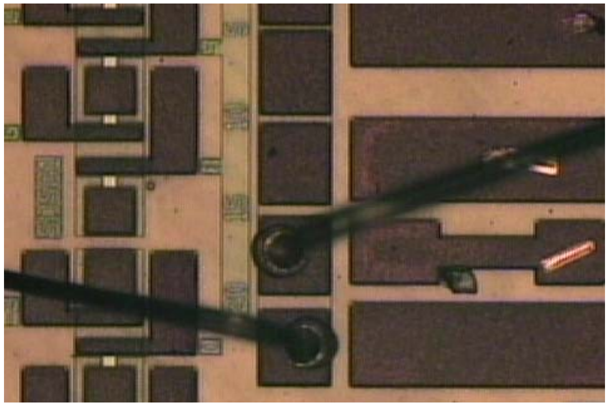


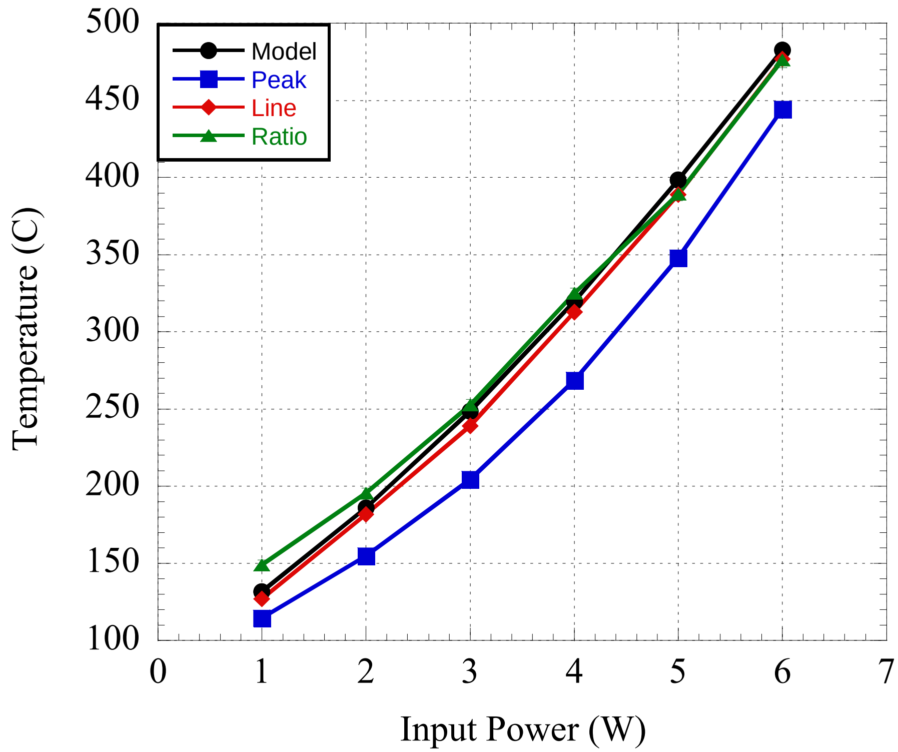
Ratio



Measurements on GaN TLM







D. Green, et al., ICNS 2007.

Data Show That:

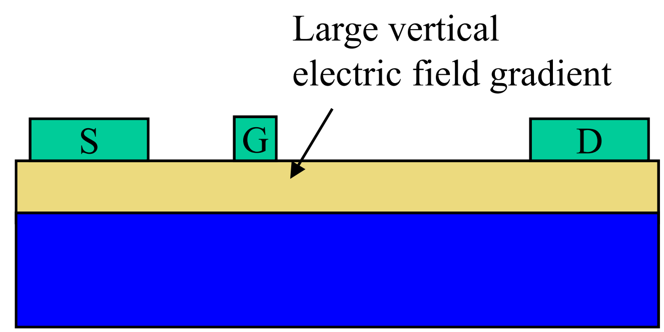
Raman Peak Shift measurements under estimate the temperature

Raman Linewidth in good agreement with FEA model and Ratio Method

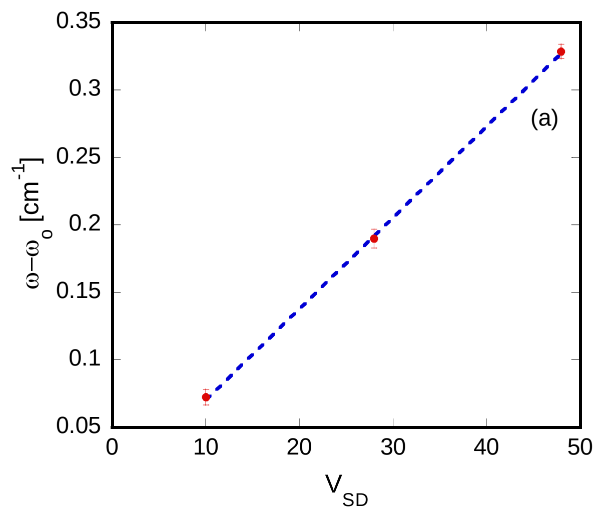
Baseplate temperature: 85°C

Stress Dependence: Inverse-Piezoelectric Effects

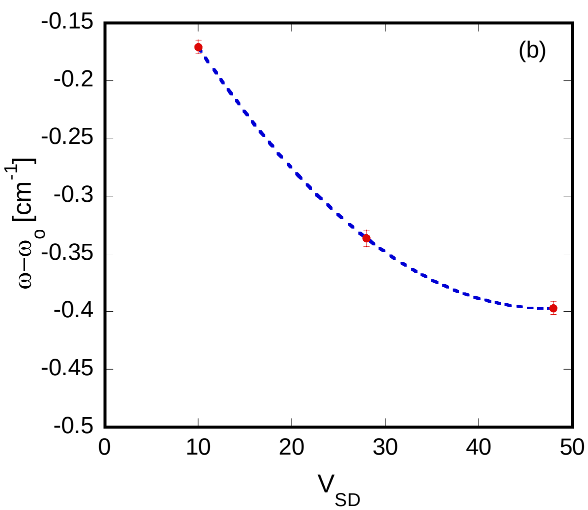
- HEMT operated under pinch-off conditions (no joule heating)
- Peak shift shows linear dependence
  - Piezoelectric induced stresses are proportional to applied bias
- Linewidth shows non-linear dependence
- <u>Conclusion:</u> Only Stokes/Anti-Stokes ratio may be used without stress induced errors



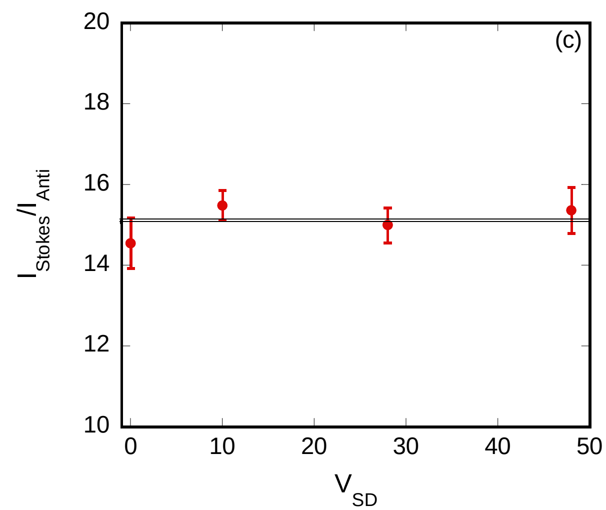
Peak Shift



Linewidth

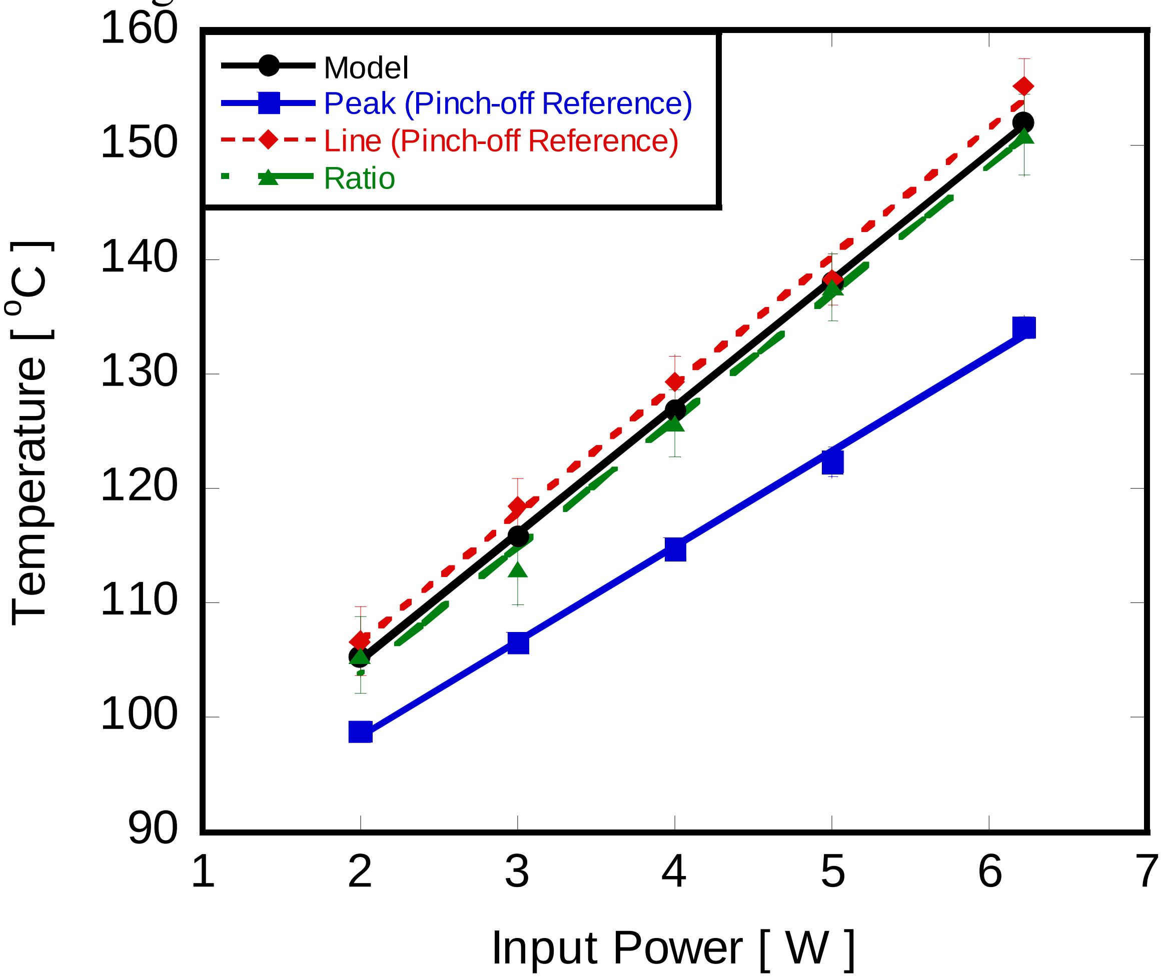


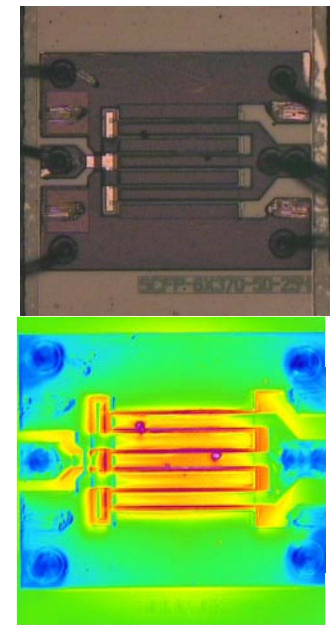
Ratio



Raman Thermometry: HEMT, Pinch Off Condition

- Piezoelectric effects may then be removed by monitoring the change in the Raman spectrum from pinch off rather than un-powered conditions. Good agreement is shown with Ratio method and model for the linewidth method.





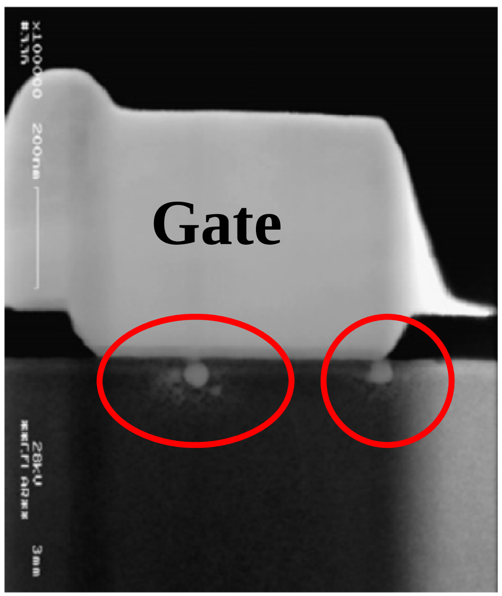
Next Step: Differences in the temperature measurements may be used to predict stress.

Converting Results into Stress

1) $$\omega_{j,T} = AT + \omega_{o,j}$$ Stokes peak shift with temperature

2) $$\Gamma_j = BT^2 + CT + \Gamma_{o,j}$$ Linewidth broadening with temperature

3) $$\omega_{j,\sigma} = D\sigma + \omega_{o,j}$$ Stokes peak shift with stress



$$\Delta\omega = A\cdot(T - T_o) + D\sigma$$

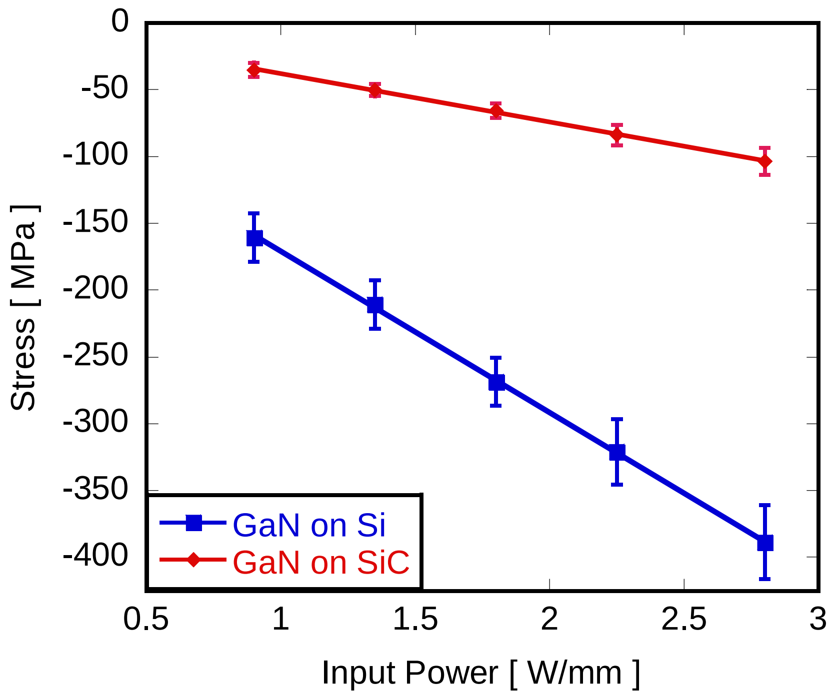
Temperature — $A\cdot(T - T_o)$

Stress — $D\sigma$

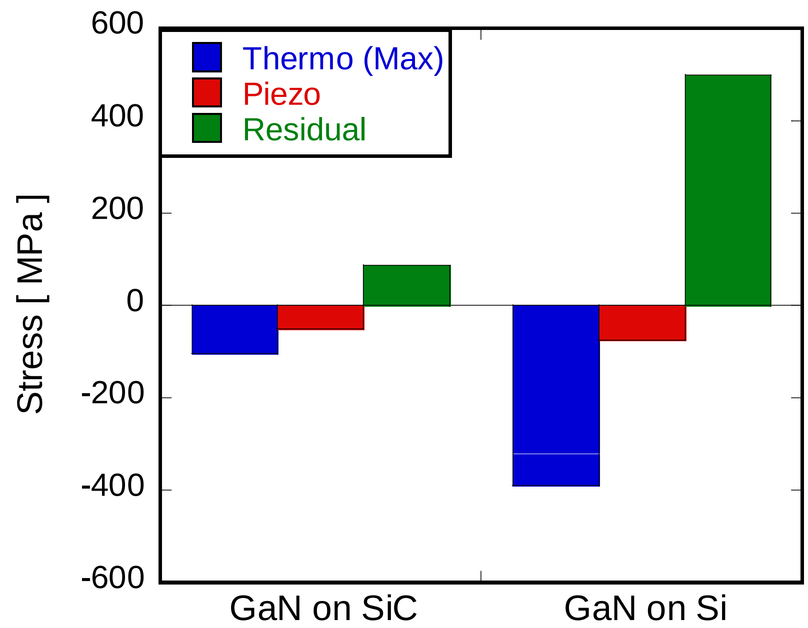
$$\sigma = \frac{(T_\omega - T_\Gamma)A}{D}$$

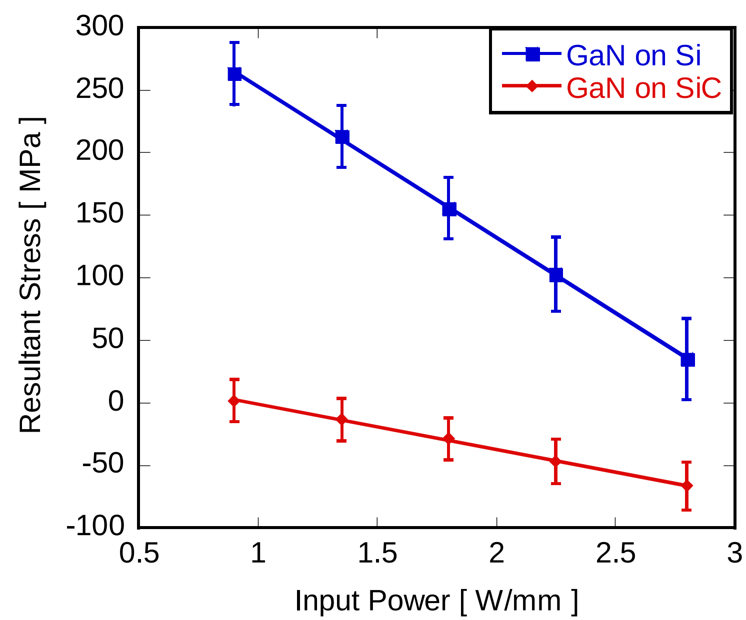
**pictures from Burgaud, Constancias, Martel, Savina, Mesnager 2007

Biaxial Stresses in Devices: GaN/SiC vs GaN/Si



THERMOELASTIC STRESS



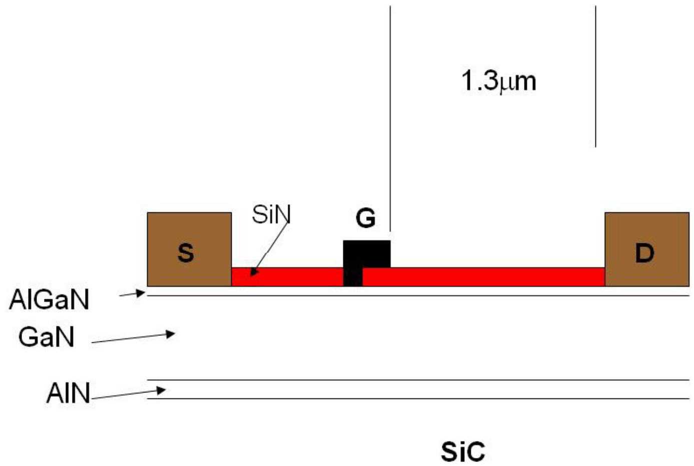


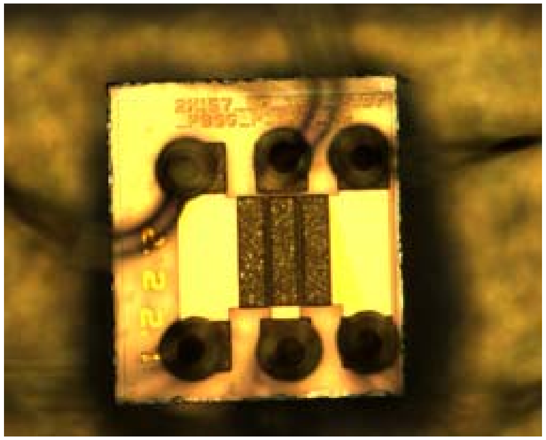
$$\sigma_{xx} = \sigma_{yy} = \left(\frac{\beta}{D}\right)\left(d_{zz} - \frac{2S_{xz}}{S_{xx} + S_{xy}} d_{zx}\right) E_{zz}$$

*Sarua et al. Applied Physics Letters, **88** 103502, 2006.*

GaN on SiC: 4.7 W/mm

Measured 2 HEMT device architectures:
2 x 167 µm gate to gate spacing: 50 µm
2 x 250 µm gate to gate spacing: 40 µm

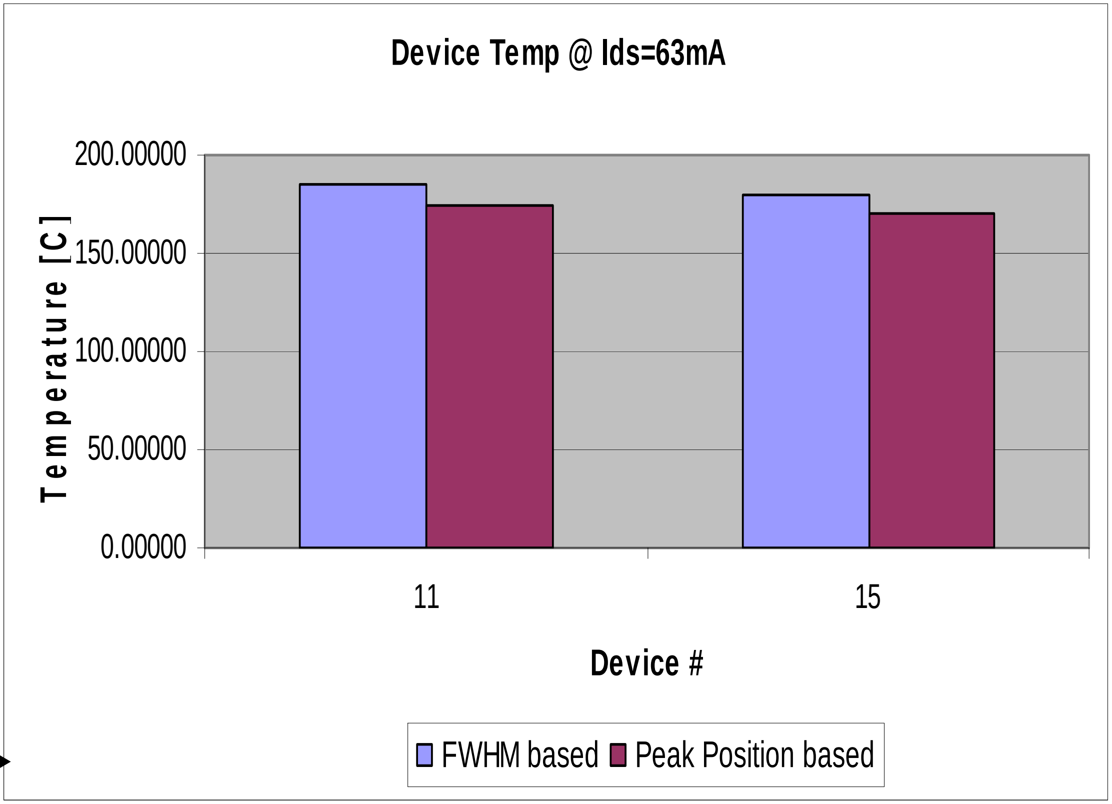




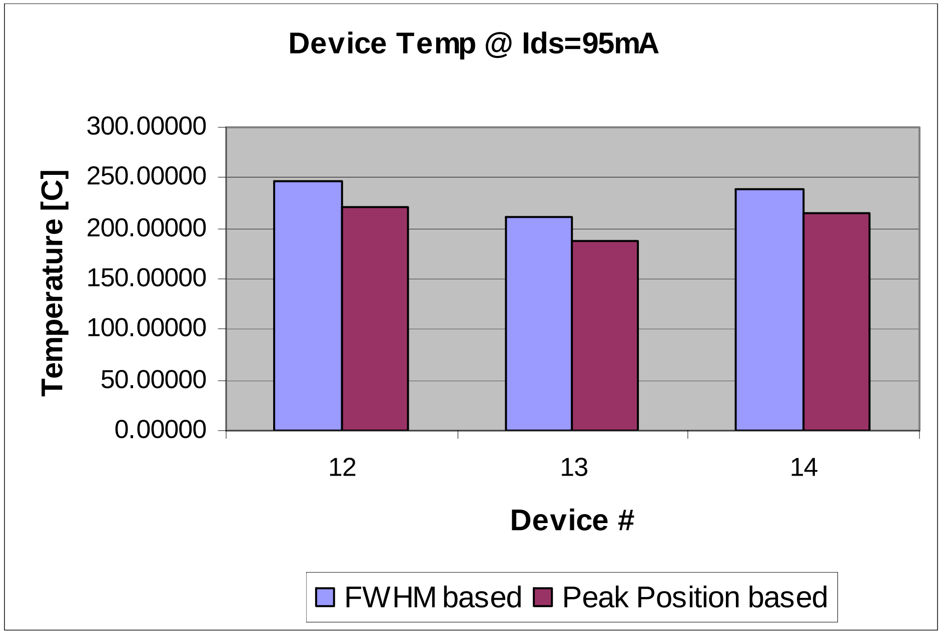
Measured at 4.7 W/mm and base plate temperature of 76°C.
(higher power than previous devices)

Pinch-off condition: Vg = -3V
Ids = 63 mA
Vds = 25V

2 x 167 devices →



Device Changes with Stressing
GaN on SiC   4.7 W/mm

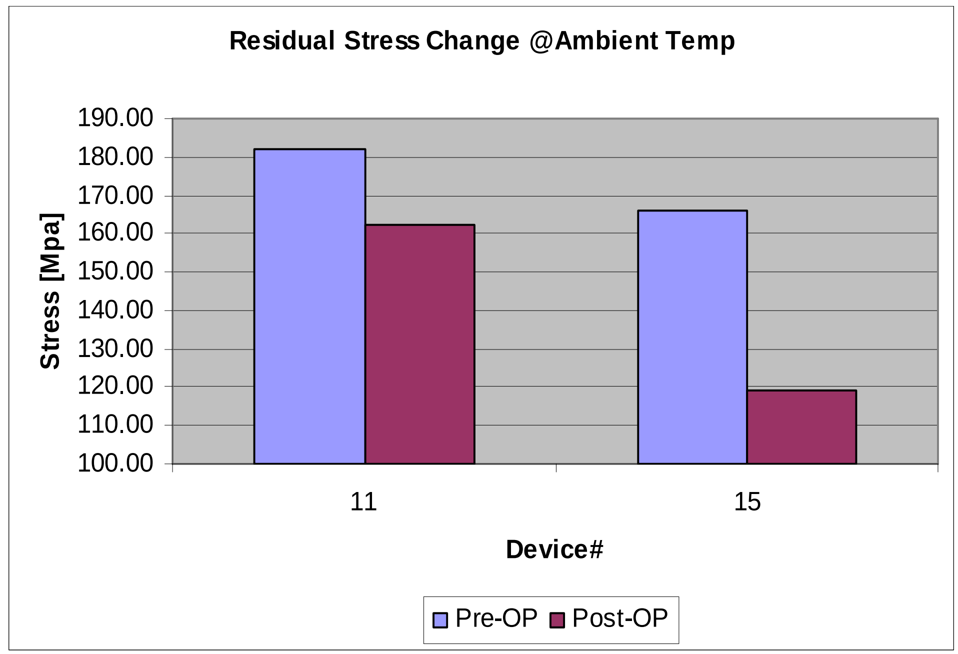


2 x 250 devices

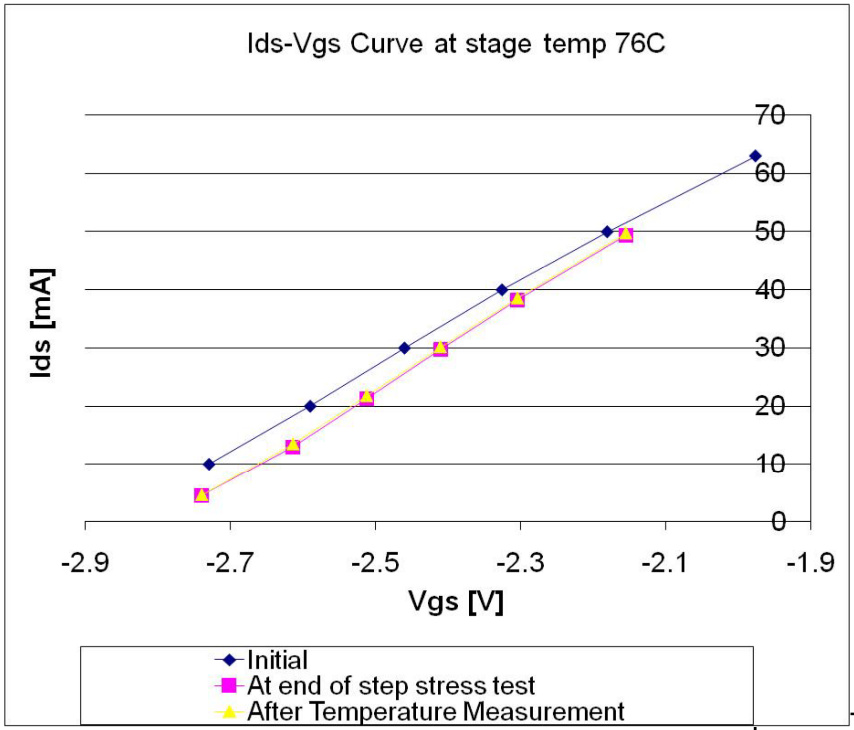
Devices run to higher powers than previous data shown (2.7 vs 4.7 W/mm).

Stress Relaxation may be occurring.
Why???

2 x 167 devices



Device Changes with Stressing



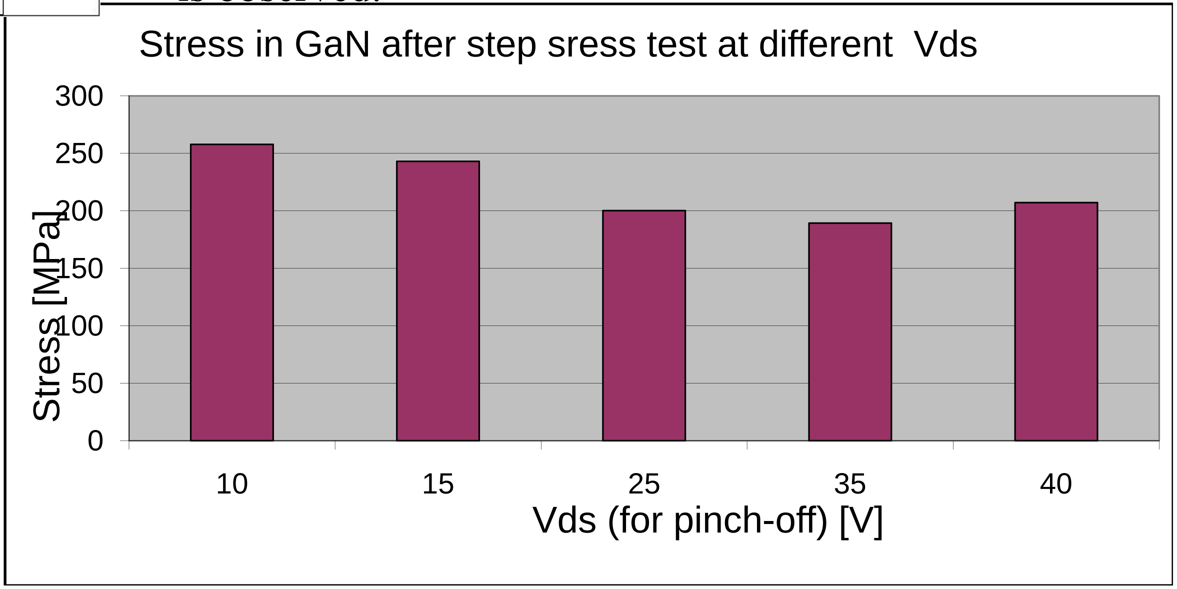
Test to determine if application of electric field or E-field plus heating impacts device.

Vds increased under pinch off conditions. Residual stress in GaN measured after each step.

I-V characteristics are different simply after applying a pinch off bias.

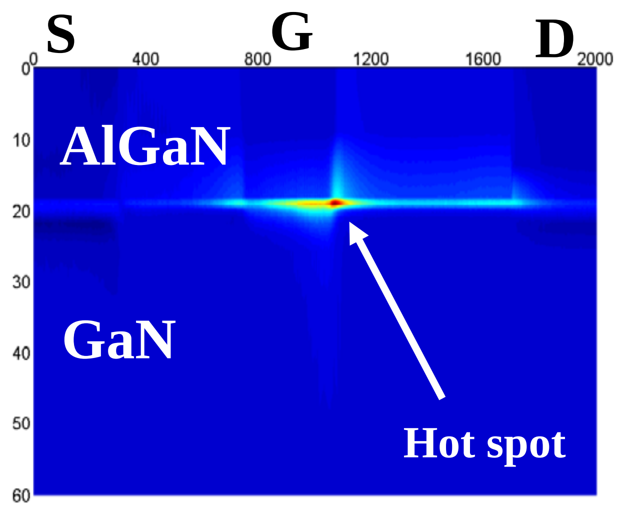
Subsequent powering of the device does not cause any additional changes in I-V

By increasing the bias, additional relaxation in device is observed.



Multiscale Thermal Modeling

Hypothesis: Non-Fourier effects can become important in heat dissipation when heat generation zone is close to Phonon Mean Free Path



Assumptions:

Gray phonon model for GaN (no optical phonon effects)

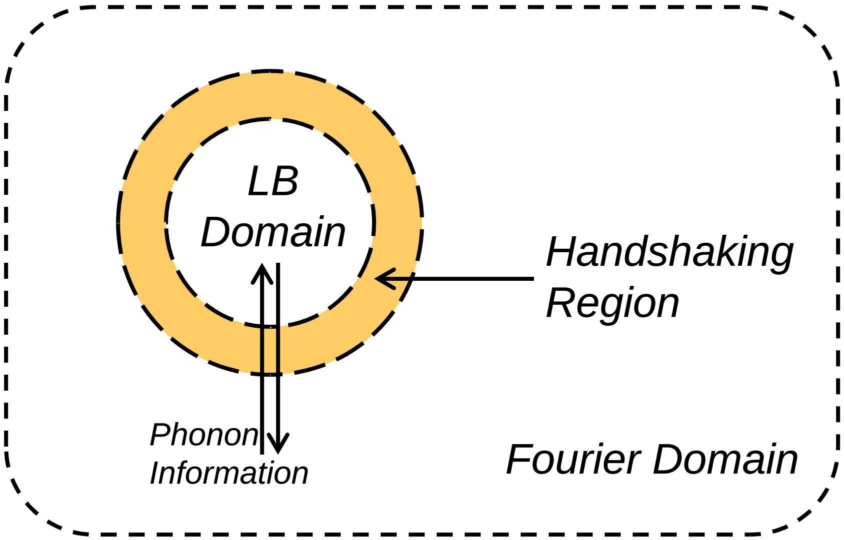
Constant temperature properties

Simulation Tool:

Lattice Boltzmann (LB) phonon transport code coupled to a finite difference (FD) solver (multiscale simulation)

Note: Multiscale LB/FD model also allows for the application of boundary conditions at macroscopic distances away from the hot spot so as not to interfere with the results

Multiscale Modeling of Heat Transport



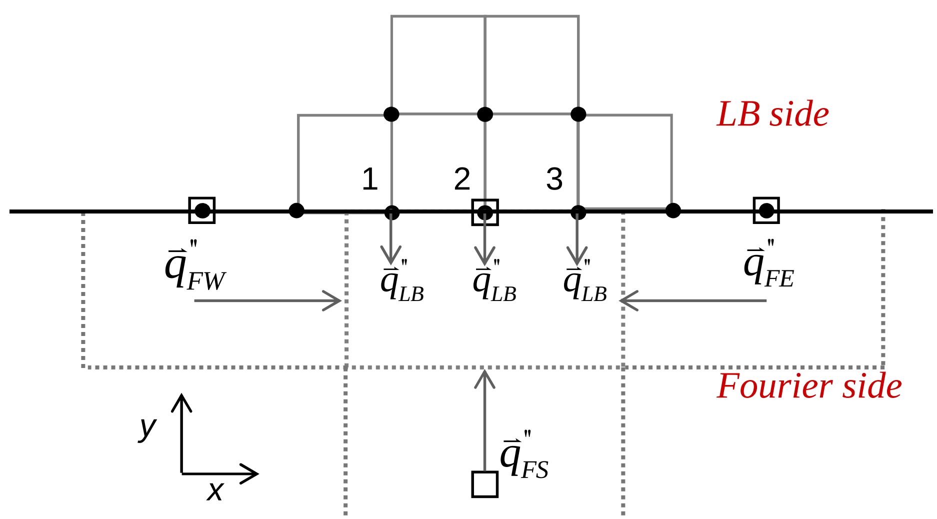
Phonon information must pass across the interface in both directions

$$q_1''(a,t) = q_2''(a,t)$$
$$T_1(a,t) = T_2(a,t)$$

Usual Restriction

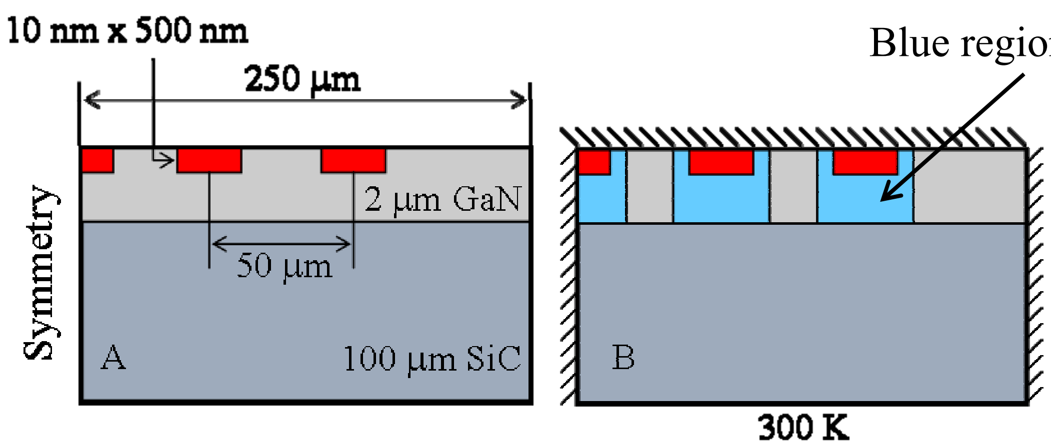
Easy to find phonon information moving from LB→FD

Harder to find the proper missing distribution function that allows phonons to travel from FD →LB

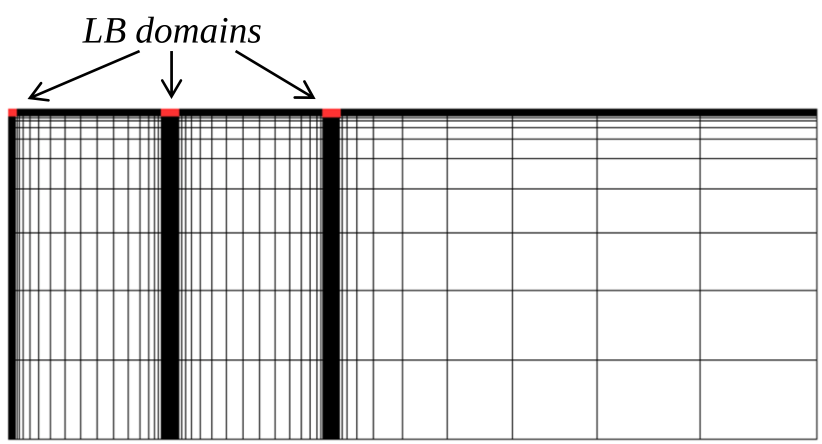


Multiscale GaN HEMT Model

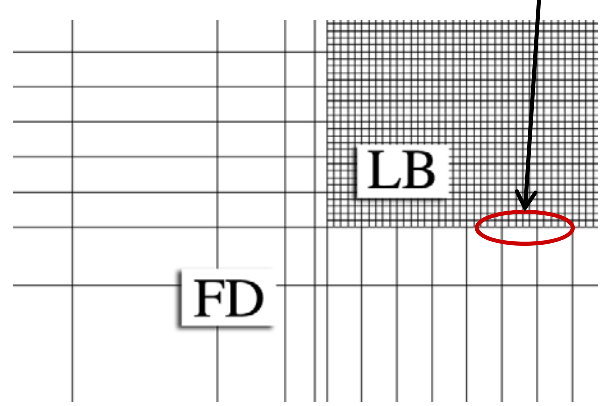
6 Finger HEMT Modeled Geometry:



Grid Expansion of 5:1 at LB/FD interface

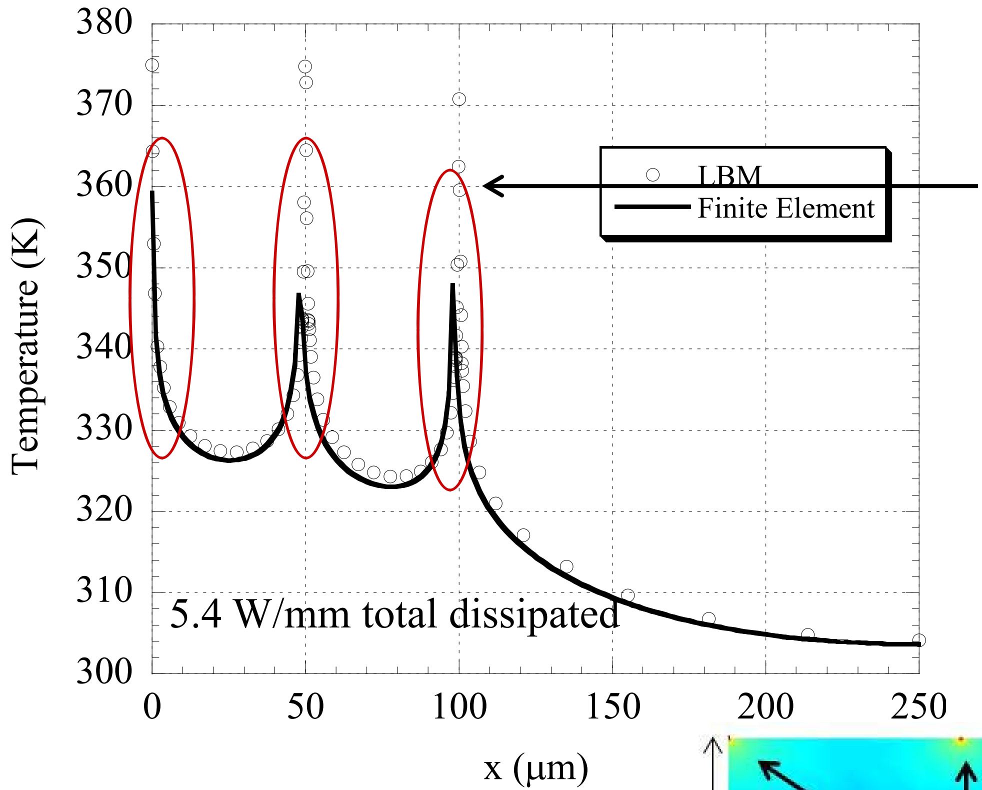


Full field mesh view



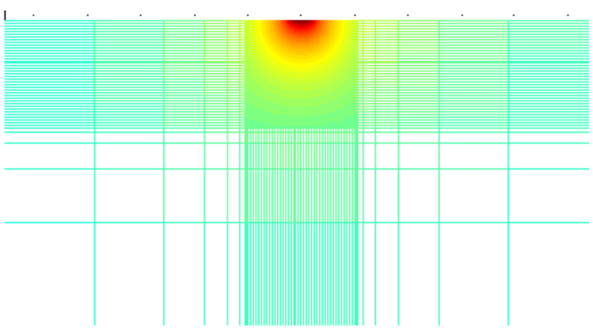
Magnified view of coupling interface

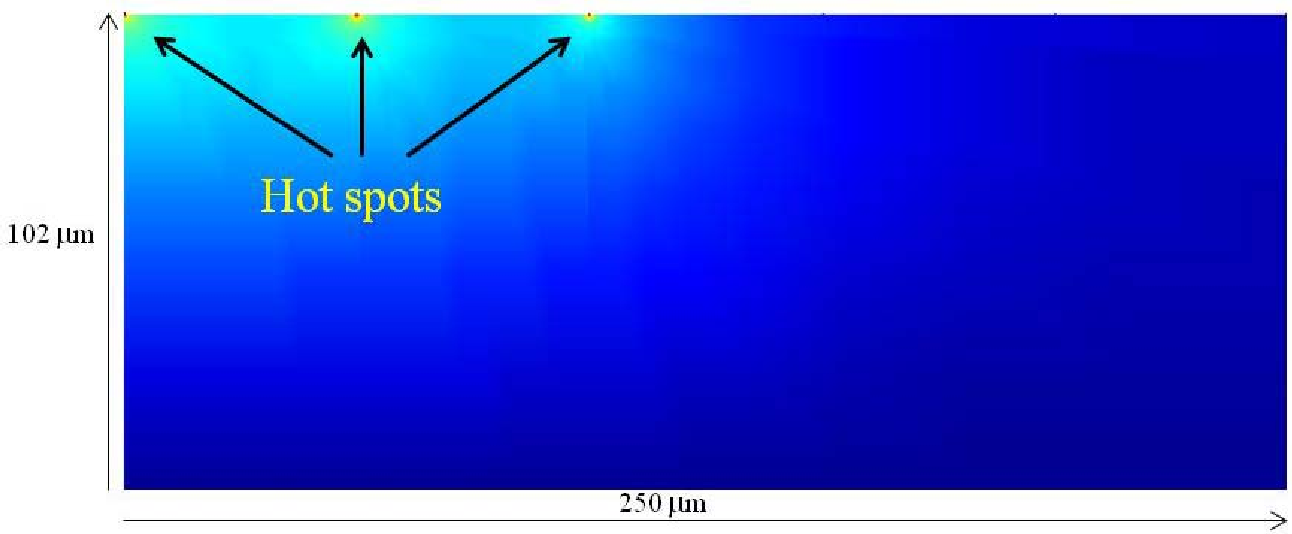
Temperature Response



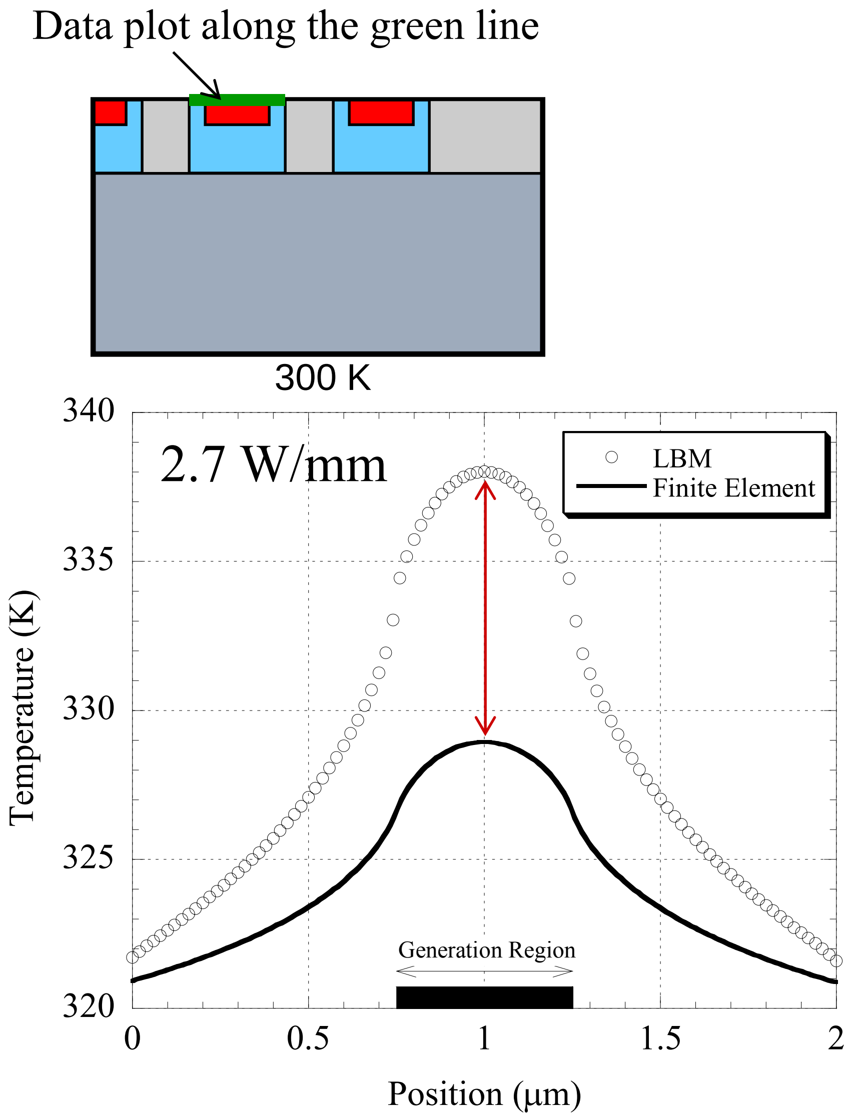
Maximum deviations occur around the hot spot

Effects of optical phonons have been ignored in these simulations

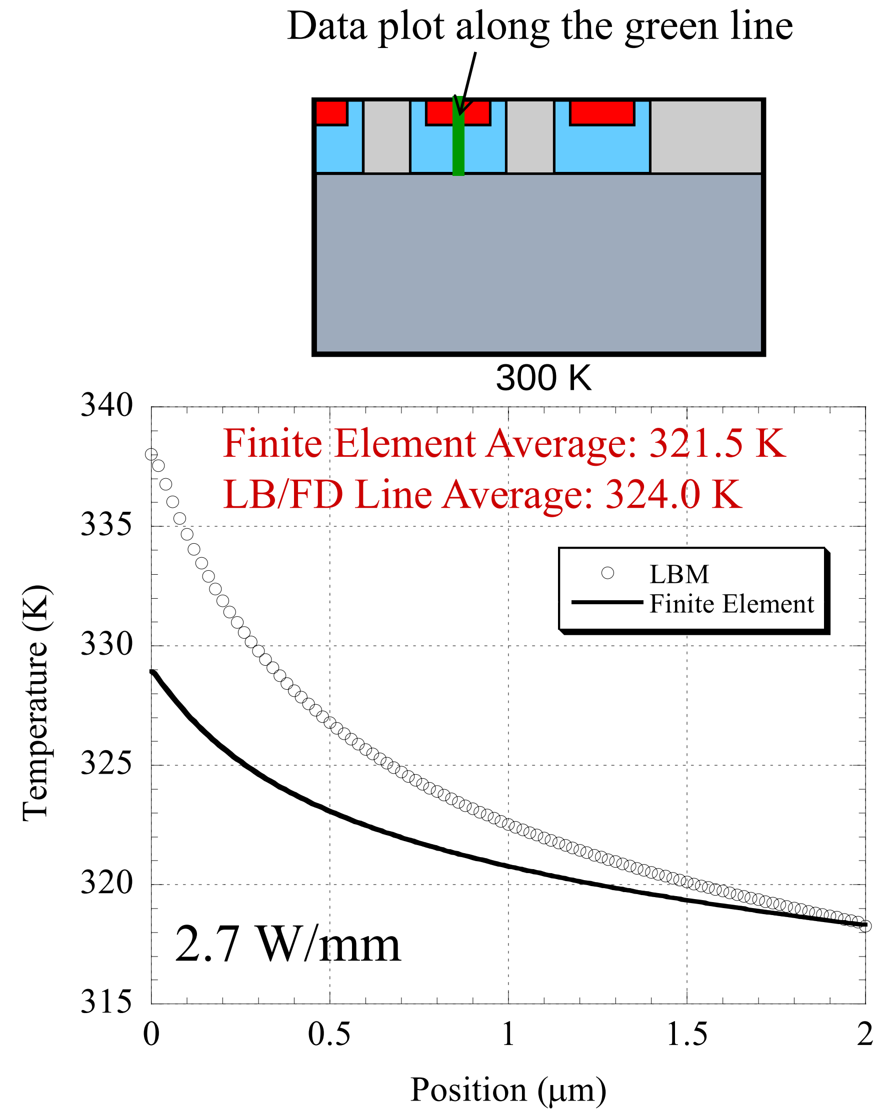




Multiscale GaN HEMT Model



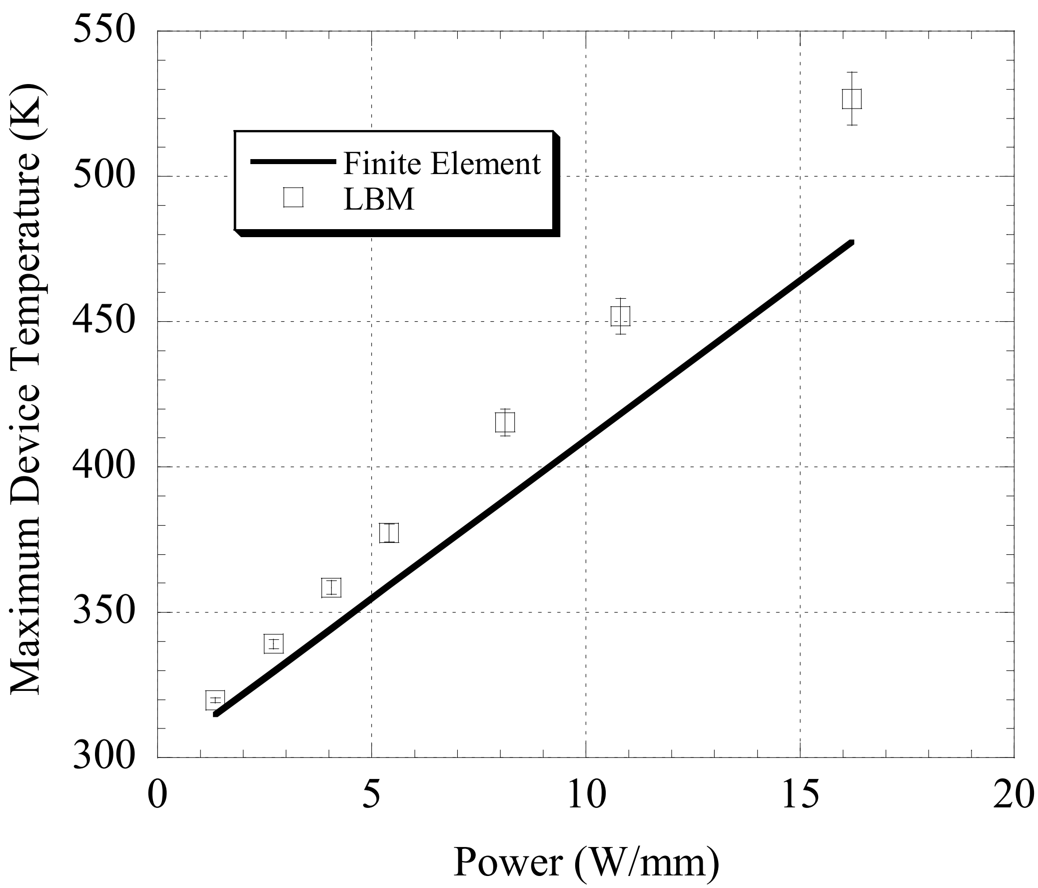
Phonons being confined in the y-direction, causes large deviations in the x direction temperature distribution



Temperature distribution relaxes back to diffusive behavior away from the hot spot

Temperature Response

What is the trend with increasing dissipated power?



At low powers, finite element and LB simulations are similar

Deviation ↑ as power ↑

Error bars reflect error introduced by the LB lattice size

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